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CHARACTERISTICS OF MACROPOROSITY IN A REDUCED TILLAGE AGROECOSYSTEM WITH MANIPULATED EARTHWORM POPULATIONS: IMPLICATIONS FOR INFILTRATION AND NUTRIENT TRANSPORT

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Summary—The effects of macroporosity on the potential for nutrient transport has been extensively studied for no-tillage agroecosystems. The present study was undertaken to quantify macroporosity and to demonstrate the potential for nutrient transport in reduced-tillage systems. Soil macropore area and numbers were quantified by image analysis into three size classes (1–8, 8–16 and > 16 mm^2) at three depths (10, 20 and 30 cm) at two locations (between-row, within-row) in corn agroecosystem enclosures with manipulated earthworm populations (reduction, not manipulated, addition). A dilute solution of latex paint was surface-applied to determine pathways for water infiltration. All macropore sizes contributed to infiltration. Earthworm-treatments had no significant effects on infiltration rates, but rates were significantly faster within crop rows than between rows. In the earthworm-addition plots the area of macropores was significantly greater in the surface soil (10 cm depth) then in the other treatments, indicating re-formation of continuous flow pathways destroyed by tillage practices. The majority of the > 16 mm^2 size pores were recognized as *Lumbricus terrestris* (L.) burrows, which represented the greatest per cent area of all size classes at the 10 cm depth. The area of these large macropores was significantly greater in addition-treatments than in the other plots at all depths and locations except for 30 cm-deep between-row locations. The absence of an earthworm effect at this location is attributed to the existence of pre-existing burrows that were not disrupted by tillage or root activity and is due to earthworms concentrating their activity in the root-zone, in the within-row location. By increasing soil macroporosity and creating transport pathways of preferential flow, earthworms potentially affect the nutrient transport in leachate and nutrient loss from the agroecosystem. © 1997 Elsevier Science Ltd

INTRODUCTION

During feeding and associated vertical migration, earthworms burrow through the soil creating horizontally and vertically continuous channels. These channels range in size from 1 to > 10 mm dia (Lee, 1985) and can be continuous to depths of 2 m or more, such as those produced by *Lumbricus terrestris* (Ehlers, 1975). These continuous channels influence infiltration of water into the soil (Beven and Germann, 1982; Germann *et al.*, 1984; Joschko *et al.*, 1989), resulting in infiltration rates up to six times higher with higher densities of earthworm-associated macropores (Ehlers, 1975). Infiltration can occur by bypass flow, preferential flow through larger soil pores, when water ponds on the soil surface (Bouma, 1991; Radulovich *et al.*, 1992; Trojan and Linden, 1992). Infiltration through these channels is important in transporting water, agricultural chemicals and nutrients through the soil (Edwards *et al.*, 1989; Edwards *et al.*, 1992; Shipitalo and Edwards, 1993). Organic matter lining earthworm burrows (Edwards *et al.*, 1992; Edwards *et al.*, 1992b; Stenhouwer *et al.*, 1994), rainfall intensity and soil-dryness (Edwards *et al.*, 1989; Edwards *et al.*, 1992a) affect transport of chemicals and nutrients. Transport of organic chemicals and nutrients to groundwater is possible if enhanced by earthworm burrowing (Edwards *et al.*, 1992a; Radulovich *et al.*, 1992; Shipitalo and Edwards, 1993).

Our objectives were to assess the effects of manipulated earthworm populations on macropore distribution, and to determine if macropores present influenced solute transport through the soil profile. We assessed infiltration rates, and pore number and area distribution at three depths to study the potential for solute transport. This study was performed in an effort to demonstrate that reduced-tillage can be as important in influencing nutrient loss as no-tillage.

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MATERIALS AND METHODS

The study site is located at the Ohio Agricultural and Research Development Center, Wooster, Ohio. Earthworm density manipulation plots are maintained on a regular basis at this facility. The field site is on a flat, homogeneous area of fine, mixed, mesic Aquic Fragiudalf soil of the Canfield series that represents a major agricultural soil type in the region. The soil is a deep, moderately well-drained upland soil with a silt loam surface texture (13% sand, 73% silt, 14% clay) and a relatively impermeable fragipan at a depth of 40–75 cm. Mean annual precipitation is 905 cm, evenly distributed throughout the year. The field was reduction tilled by disking to a depth of 10 cm, and was planted with a summer crop of corn, mid-June 1993.

The experimental design consisted of a randomized block design involving four replicated blocks. In each block, three plots were randomly assigned one of three nutrient inputs, applied at N-equivalent of 150 kg ha^{-1}: an inorganic fertilizer (NH_4NO_3), straw-packed cow manure, and alfalfa hay. In each main plot (20 m × 30 m), there were three 20 m^2 enclosures bordered by 50 cm-deep physical barriers. In each enclosure, the three earthworm treatments were: (1) unmanipulated earthworm populations (control); (2) reduction-treatment, (electroshocking); (3) addition-treatment, (manual addition of earthworms). Earthworms were added in the relative percentages of species existing in the control (see Bohlen *et al.*, 1995 for earthworm population data). In each enclosure, infiltration rates and macropore characteristics were analyzed in two replicate areas. Each replicate had two cores (four total) to test the effect of location; one core was located within the crop row (within-row) and the other between the crop rows (between-row), with at least 5 cm between cores. The field was disk-plowed once prior to the planting of corn, several weeks before sampling occurred.

Infiltration rates were measured once, on one day, in early July, 1993. In each enclosure, four 15 cm-dia cores were placed into the soil to a depth of 4 cm. This depth insured a seal between the core and the ground, minimizing or eliminating water leakage. Rulers were placed inside the cores and paint was added (a 1600 ml mixture of 1400 ml water and 200 ml inert latex paint) and allowed to infiltrate until a drop of 5 cm in the level of paint. Time for infiltration was measured, but was limited to 5 min, at which time the change in level was recorded. Paint was used to mark the passage of water through the soil.

Macroporosity was measured for 8 days, in mid-July, in the exact area of infiltration measurements, using a 15 cm-dia core placed to a depth of 35 cm. Cores were inverted onto poles with a 15 cm dia wood disk nailed to the top to prevent the soil from falling out. The soil was extruded to depths of 30, 20 and 10 cm by pulling down on the corer while the soil was held in place by the disk. Extruded soil was shaved off at these depths and vacuumed to provide a clean and smooth surface upon which transparent acetate sheets were placed. The inside area of all visible pores > 1 mm dia were marked with two different colored markers to distinguish between painted and non-painted pores. Non-painted pores that were not visibly continuous were not mapped.

The acetate sheets were analyzed using a software-based video image analysis system (Image Plus Systems produced by Scientific Micro Programs). The program was run on a Dapple Systems computer with Scientific Micro Programs Disc Management System. The program produced a binary image of the marked pores and calculated the surface area of each individual pore. The data are presented as mean percent pore area of each core (177 cm^2) and mean pore numbers m^{-2}. The three size classes chosen were based on inflection points of cumulative curves for area and represent pores with areas 1–8, 8–16 and > 16 mm^2, which have equivalent circular diameters of 1.1–3.2, 3.2–4.5 and > 4.5 mm, respectively.

Infiltration rates were analyzed with a 3-way ANOVA, with nutrient treatments as whole plots and earthworm manipulations and core locations as subsequent split plots. The macropore data was analyzed with a 4-way ANOVA, with depth as an additional split plot. Correlations were performed on both infiltration data and macropore data. There were no significant nitrogen-earthworm treatment interactions. Therefore, our analysis will only present earthworm treatment, location and depth effects.

RESULTS AND DISCUSSION

Infiltration occurred under contained ponded conditions in the area under the core and included lateral subsurface flow. Infiltration rates were not significantly affected by earthworm treatments, but were significantly faster within-row (1.409 cm s^{-1}) compared to between-row locations (1.041 cm s^{-1}; n = 36, F = 6.24, P=0.019, d.f. = 1). The within-row locations have live and dead root channels that can increase infiltration rates (Beven and Germann, 1982). Compaction of the soil would affect the between-row infiltration rates, but our measurements were confined to non-traffic areas. Indications of infiltration were evident at all depths in all the earthworm treatments, particularly in reduction-treatments which do not have active earthworm populations to re-form burrows destroyed by tillage. Infiltration has not been previously evident below the plow layer (Ehlers, 1975; Logsdon *et al.*, 1990). In the reduction-treatment, infiltration could

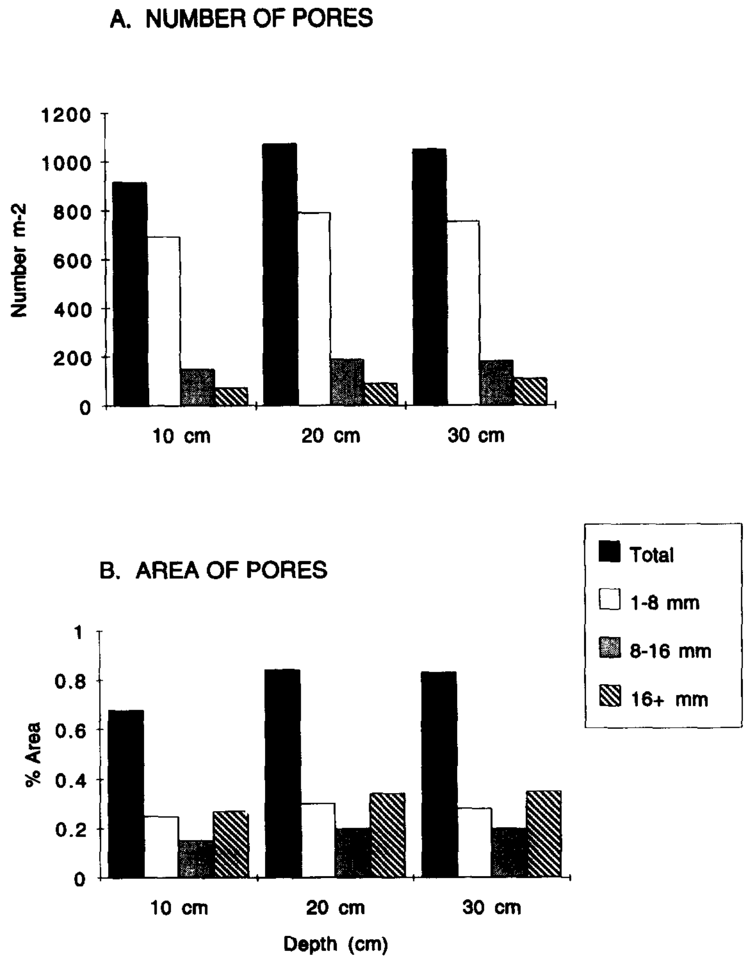

Fig. 1. Size class distribution of soil macropores for each depth showing numbers of pores per m^2 (A) and the average per cent area (B).

not have occurred through pores continuous with or open at the soil surface, directly contradictory to previous findings (Ehlers, 1975). It is smaller sized pores, which are more abundant at 10 cm (Fig. 1A), that possibly provide these continuous pathways for infiltration.

Macroporosity is indicated by number of pores and percentage of area occupied by pores. Macroporosity was lower at 10 cm, although not significantly, than at 20 and 30 cm (Fig. 1). These findings are consistent with previous studies (Ehlers, 1975; Aina, 1984; Edwards *et al.*, 1988b). Of the total number of macropores at all depths 74% were of the smallest size class (1–8 mm^2) with the two larger size classes contributing only a small portion (Fig. 1A). Pore number averaged 746, 174 and 92 m^{-2}, respectively, for the 1–8, 8–16 and > 16 mm^2 size classes, over all depths. Macropores in the addition-treatments averaged 124 m^{-2}, and are consistent with numbers found in no-tillage systems (e.g. 145 m^{-2}; Edwards *et al.*, 1988a). The largest pores (> 16 mm^2), although fewest in number, occupied the largest per cent of total area; up to 8% greater than the 1–8 and 8–16 mm^2 size classes over each of the three depths (Fig. 1B). Per cent pore area averaged 0.28, 0.19 and 0.32%, respectively, for the 1–8, 8–16 and > 16 mm^2 size classes over all depths. These pores are the result of biological forces and can contribute to infiltration (Edwards *et al.*, 1988b; Edwards *et al.*, 1990).

Table 1. Effects of earthworm treatments on area and number of total pores and > 16 mm^2 pores over all depths

Treatment	Total No. m^{-2}	No. m^{-2} > 16 mm^2	Total % area	% > 16 mm^2
Reduction	940.5^a	72.66^a	0.68^a	0.24^a
Control^c	1015.5^a	79.38^a	0.74^a	0.27^a
Addition	1081.9^a	124.18^b	0.92^b	0.44^b

^{a,b}Different superscripts within a column indicate significant difference at $P \leq 0.05$.

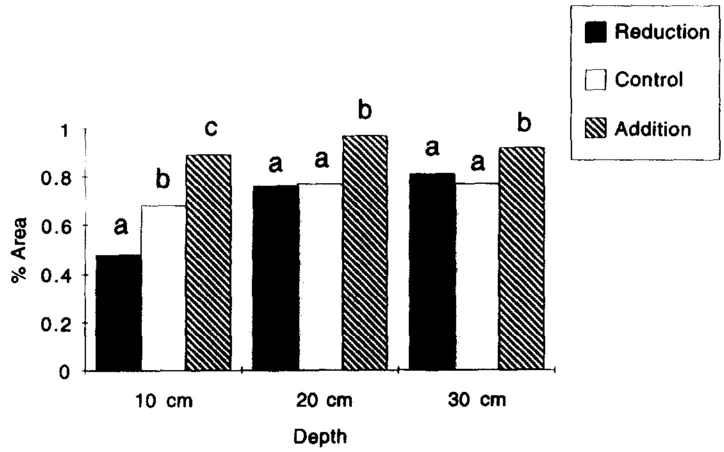

Fig. 2. Macroporosity given by per cent area of total pore area by depth for each earthworm treatment. For a given depth, different letters indicate significant differences at $P \leq 0.05$.

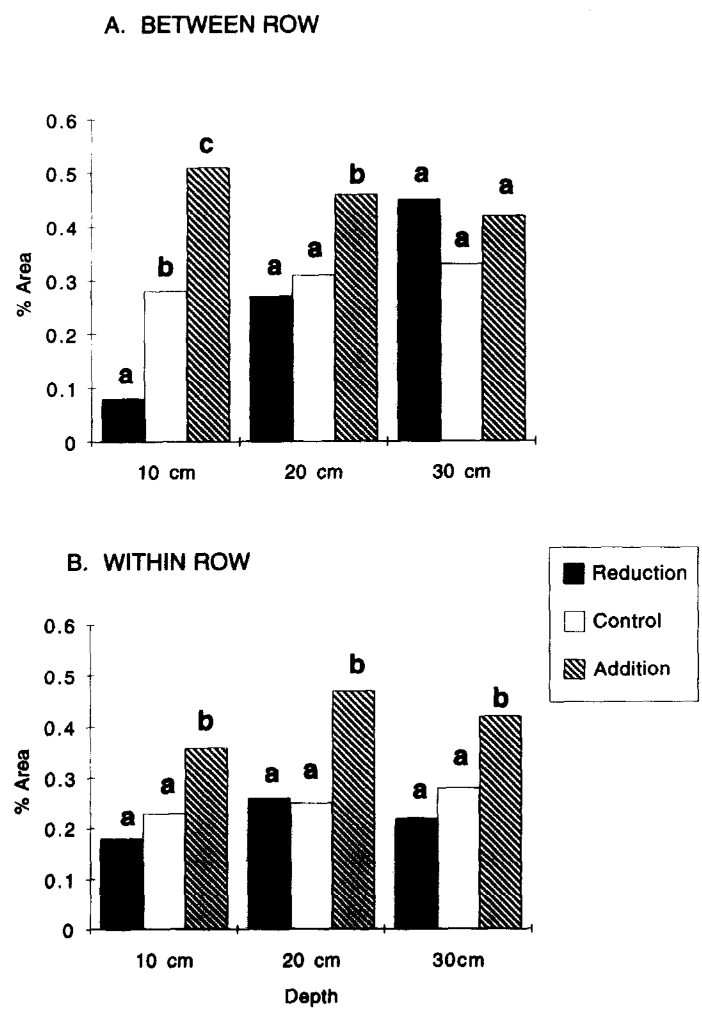

Fig. 3. Macroporosity given by per cent pore area for the > 16 mm^2 size class by location: (A) between-row; (B) within-row; and depth. For a given depth, different letters indicate significant differences at $P \leq 0.05$.

Earthworm addition-treatments significantly increased numbers of pores $> 16\,mm^2$, total pore area, and area of pores $> 16\,mm^2$ compared to reduced- or unmanipulated (control) treatments (Table 1). The increase in macroporosity in the addition-treatments was largely due to an increase in the largest size class of macropores (Table 1). The presence of earthworms, incorporation of organic matter into the walls of the burrows, or the presence of earthworm casts allowed us to identify the majority of these larger macropores as *Lumbricus terrestris* burrows. For total pore area, the addition-treatment had significantly higher percentages of macropore area at all three depths (Fig. 2). For macropore area $> 16\,mm^2$ in the within-row location, the addition-treatment was also significantly greater than other treatments for all depths (addition > control = reduction; Fig. 3B). This occurred in the between-row location at 10 and 20 cm depths (at 30 cm-deep addition = control = - reduction; Fig. 3A). Only at 10 cm was the per cent area significantly different between all three earthworm-treatments for total pore area (Fig. 2) and pore area $> 16\,mm^2$ in the between-row location (addition > control > reduction; Fig. 3A). The earthworm-treatment effects at 10 cm demonstrate that large macropores destroyed by tillage must be re-formed by earthworms whereas macropores are not being re-formed in the reduction-treatments (Fig. 2; Fig. 3A). When considering macropores deeper in the soil, pre-existing burrows can not be disrupted by tillage (Edwards *et al.*, 1988a; Edwards *et al.*, 1992). Root activity can destroy pre-existing burrows as well. However, root activity and resulting increased earthworm activity, in the root-zone, can indirectly cause new channels to be formed. This happens in the within-row locations only, whereas fewer burrows are formed between-row. The greater per cent area of macropores at all depths in the addition-treatment within-row suggests that burrows were re-formed by earthworms (Fig. 3B). Macropores that are deeper in the soil can remain intact only between crop rows because root activity has a profound effect of increasing within-row earthworm activity. Further studies should be undertaken to investigate this phenomenon.

Various investigators have identified that macropores are pathways for solute transport. In this study, macropores 1 to $> 16\,mm^2$ contributed to solute transport as indicted by painted pore walls to depths of 30 cm. Reduced-tillage has not hindered solute transport in macropores. Infiltration rates were increased in locations within crop rows, where earthworm activity is increased by the root-zone. Earthworms in these locations can potentially influence infiltration and solute transport. The influence of macroporosity on infiltration has been underestimated, however, because horizontally-continuous macropores exhibiting lateral flow were not characterized. This has presumably obscured some effects of the earthworm treatments, as well.

The transport of solutes through macropores has been extensively studied in no-tillage systems (Edwards *et al.*, 1989; Edwards *et al.*, 1992; Shipitalo and Edwards, 1993). Some studies have shown that nutrients can be leached off the soil surface and down into macropores (Edwards *et al.*, 1989; Edwards *et al.*, 1992a; Shipitalo *et al.*, 1990) Large earthworm populations in reduced-tillage systems increase the macropore numbers, and consequently nutrient loss through leaching. Thus, a switch from no-tillage to a reduced-tillage management system, for elimination of nutrient loss will have to be carefully considered if earthworm populations are at abundances high enough to increase macroporosity and influence nutrient transport.

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